# Numerical analysis of the dynamics and the rapid solidification on splat formation during thermal spray process using the finite element method

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## Résumé :

*La méthode des éléments finis est utilisée pour simuler le processus de dépôt par projection thermique. pour résoudre les équations de la dynamique des fluides et de conservation de l'énergie on a utiliser la méthode eulérienne à grille fixe VOF . Un algorithme de volume de fluide(VOF) a été utilisé pour suivre les déformations de surface libre . pour le phénomène de solidification la méthode de chaleur spécifique équivalente (SHM) est utilisé. Une comparaison du modèle actuel au modèle expérimental et numérique disponibles dans la littérature est faite. Une série de calculs numériques est réalisée pour étudier l'effet de la problématique liée à la solidification lors de l'impact de deux gouttes identiques d'aluminium; impact successivement sur le même point et décalés dans le temps, sur un substrat en acier doux, et l'effet de la température du gaz environnant sur la formation des lamelle. Il a été constaté que les particules fondues qui se propagent successivement et la variation de la température du gaz environnant ont une grande influence sur la morphologie des lamelles, et donc la qualité de l'empilement.*

## Abstract :

*Abstract : A finite element method is used to simulate the deposition of the thermal spray coating process. The model applied a fixed-grid Eulerian control volume method to solve the fluid dynamics and energy conservation equations. A volume-of-fluid algorithm was used to track free surface deformation.The specific heat method (SHM) is used for the solidification phenomenon. A comparison of the present model with experimental and numerical model available in the literature is done. A series of numerical calculations is carried out to investigate the effect of the problem related to solidification during impact of two identical drops of aluminum; impacting successively on the same point and time-shifted,on a smooth steel substrate, and the effect of the surrounding gas temperature on the splat formation. It was found that the melt particles that spread successively and The variation of the surrounding gas temperature have a great influence on the morphology of the spread, and therefore the quality of the multilayer.*

## Keywords:

**Coating, impact, successive, rapid solidification, numerical simulation, VOF, equivalent specific heat.**

## 1. Introduction :

A thermal spraying is surface treatment method. It is used for protecting surfaces against wear, corrosion and thermal barrier. Thermal spraying can provide thick coatings (approximately 20µm to several mm). Coating materials available for thermal spraying include metals, alloys, ceramics, plastics and composites.Generally; the coating quality increases with increasing particle velocities [1-2]. Several researches have been done in this area in order to optimize and control the complicated phenomenon existed in the thermal spray processes [3].The properties of thermal sprayed coatings are essentially linked to the structure of a single splat and the quality of contact between the pilled-up splats. These properties of adhesion and cohesion and thermo-physical properties are related to the morphology of the individual splats and to the contact quality between these splats and the substrate. Experimental works have been devoted for studying an individual splat for better understanding of the different mechanisms which govern its faltering and solidification [4]. Other

researchers have studied numerically the splat formation phenomenon [5]. These numerical models take into account the hydrodynamic aspects of the splat formation and the heat transfer between the splat and the substrate. They use the volume of fraction method (VOF) [6].Abdellah El-Hadj et al. [7] adopted numerical approach to investigate the significance of surrounding gas temperature on splat morphology and the adhesion of splat on the substrate. A higher gas temperature was found to provide better adhesion. By integrating finite element method with volume of fluid and specific heat method, Zirari et al. [8] found that melting state of the particle had significant effects on the morphologies of the splat.
In thermal spray process, the surrounding gas can reach a high temperature in vicinity of the substrate (Figure(1)). Thereby, it is necessary to study the splat formation under different surrounding gas temperatures around the particle. The Galerkin finite element method is used to solve the set of governing equations using Ansys/Flotran code. The VOF method is used to track the free surface deformation. In this study, some pertinent parameters that influence the quality and the morphology of the deposit (the spread factor, the impact pressure and the temperature histories in the affected zone of the substrate) are considered.
in the second practice of this paper is to study numerically the impact of two identical drops of aluminium shifted on the same point and time-shifted on a smooth steel substrate, with the four states where such fusion drops will occur shown in diagram form in Figure (6).

## 2.1 Dynamic model

In the VOF method, the cell containing a fluid is governed by the following equations [9]:

$$\vec{\nabla}\left(\alpha.\vec{V}\right) = 0 \qquad (1)$$

$$\frac{\partial\left(\alpha.\vec{V}\right)}{\partial t} + \left(\alpha.\vec{V}.\vec{\nabla}\right)\vec{V} = \frac{-\alpha}{\rho}\vec{\nabla}p + \alpha\nu\nabla^2\vec{V} + \frac{\alpha}{\rho}\vec{F}_b \qquad (2)$$

Where $V$ is the velocity vector, ρ is the density, $p$ is the pressure, α is called fraction of fluid volume, ν is the kinematic viscosity and t the time. $F\ b$ is the body force applied to the fluid. The surface tension is an important parameter that contributes in the deformation of the droplet. It is considered as a volume force applied to the free surface of the liquid. The electrostatic forces between the molecules of the surrounding gas are very small compared to those of the liquid due to their molecular distances. The resultant of the forces is directed toward the inside of the particle. This force characterizes the liquid surface tension (σ en N/m). The liquid evolves spontaneously to minimize its surface tension (its free surface energy).
According to the VOF methodology, the fraction of fluid volume α is used for the all domain where its value indicates the presence or the absence of the fluid. We attribute the value of 1 for a point occupied by the metal and 0 in the other domain part. The mean value in the element presents the function of the fluid volume occupied by the metal [9]:

$$\alpha = \begin{cases} 1.inside.the.fluid \\ 0\langle\alpha\langle 1.Contain.a.free.surface \\ 0.empty.cell \end{cases} \qquad (3)$$

The element with a value of α between 0 and 1 is containing the free surface or the interface.
To find α(x,t) for all points of the domain it necessary to solve the transport equation [9]:

$$\frac{\partial\alpha}{\partial t} + V.\nabla\alpha = \frac{d\alpha}{dt} \qquad \text{With } \alpha(x,0) = \alpha_0(x) \qquad (4)$$

## 2.2 Heat transfer model

The SH Method is used in order to take into account for the phase changing in the metal particle. This formulation uses the equivalent specific heat which takes in account the latent heat in the energy equation as [7]:

$$\frac{\delta(\rho h)}{\partial t} = \rho c_p \frac{\partial T}{\partial t} - \rho L_f \frac{df_s}{dT}\frac{\partial T}{\partial t} = \rho c_p^{eq}\frac{\partial T}{\partial t} \qquad (5)$$

Where $h$ is the enthalpy, $T$ is the temperature, $c_p$ is the metal specific heat, $c_p^{eq}$ is the equivalent specific heat, $Lf$ is the latent heat of fusion and $fs$ is the solid fraction.

# 3.Results and discussion

## 3.1 the effect of the gas temperature

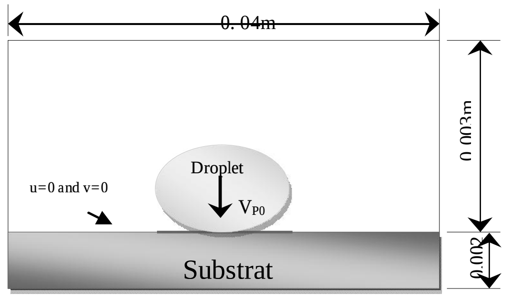



FIG.1-Physical domain of 3.92mm droplet impacting a substrate.

Numerical simulations have been performed first to validate our model. Comparison with available experimental and simulation results of Ghafouri-Azar et al. [10] is done for this purpose. An Aluminum alloy 380 particle of 3.92mm in diameter with the impact velocity of 3m/s projecting onto flat H13 tool steel substrate at initial temperature of 200°C is used. The initial particle temperature is taken above the melting temperature as 630°C. The computer generated images of sequential impact of the particle is shown in the figure (2). The shape of the flattering behavior is similar to those of the experimental results. In order to obtain a better quantitative comparison between the different models, the predicted values of the spread factor ($\xi$) is considered. This factor is calculated by normalizing the diameter $D_P$ measured from images by the initial diameter $D_{P0}$ ($\xi$=$D_P/D_{P0}$). Figure (3) shows the evolution of the spread factor of the present model compared to the measured and predicted ones of Ghafouri-Azar et al. [10]. The discrepancy between the two numerical models is due to the different methods used.

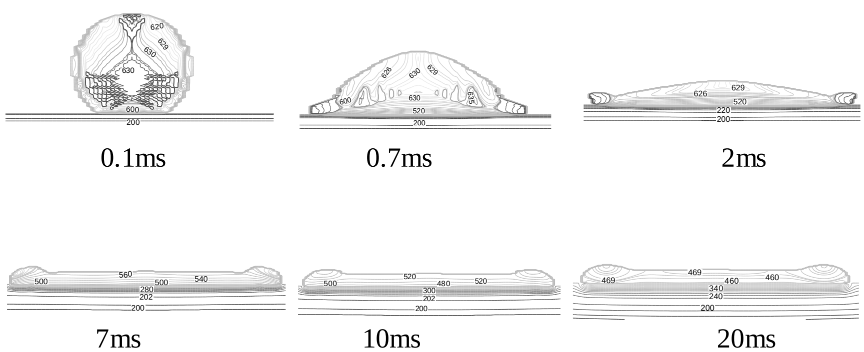



FIG.2-Representation of the distribution of the temperature of aluminum droplet (3.92 mm of diameter) for gas temperature of 300°C

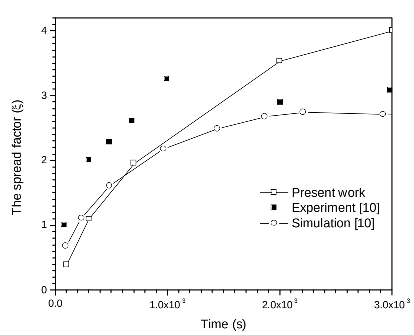



FIG.3- The spread factor of the aluminum droplet

A series of numerical calculations shows that the temperature of the surrounding gas ($T_{gas}$) can influence significantly the spreading and the morphology of the splat. the figure (4), shown which displays histories of the spread factor for different $T_{gas}$. This factor is measured as contact region of the splat with the substrate.

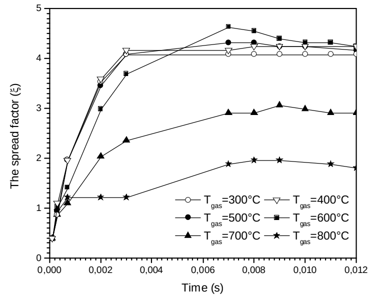



FIG.4-The spread factor for a particle impact for different gas temperature

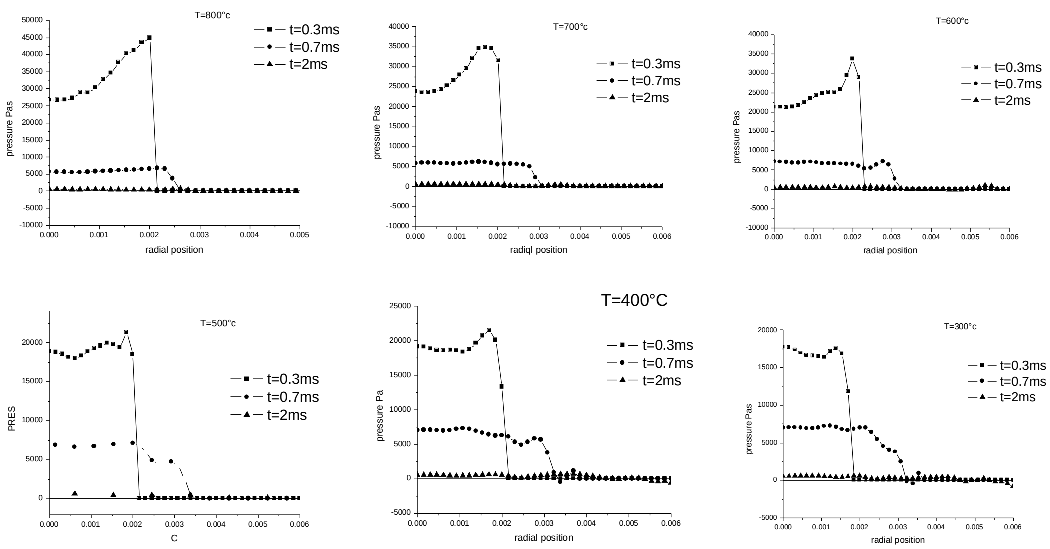
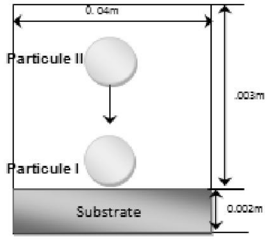



FIG.5-the variation of the contact pressure depending on the temperature of the jet

Figure 5 presents the calculated pressure distributions under the droplet at t=0.3, 0.7 and 2ms for gas temperature from 300°C to 800°C at the same times. Initially (t=0.3ms) there is a high pressure region under the splat. For $T_{gas}$=300°C, the contact pressure remains constant (~16kPa) and decreases rapidly to zero. For $T_{gas}$=800°C, the contact pressure increases from the center of the splat (~27kPa) to its frontier (~45kPa), and finally it decreases rapidly to zero. This increase in the value of pressure for a high gas temperature case can lead to improvement of adhesion of the splat to the substrate.

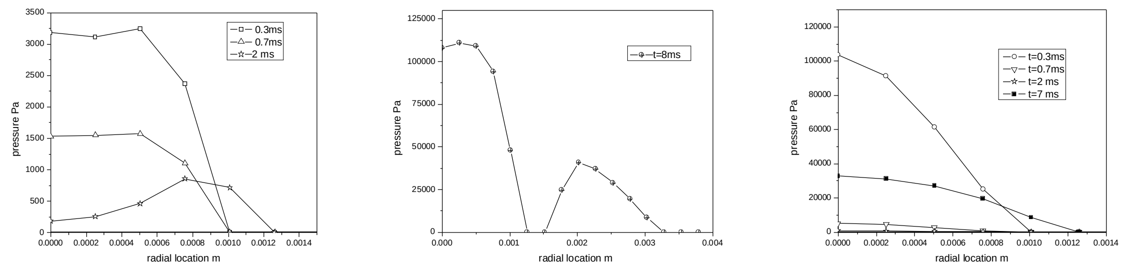
## 3.2 the effect of the molten state of two successive Aluminum particles



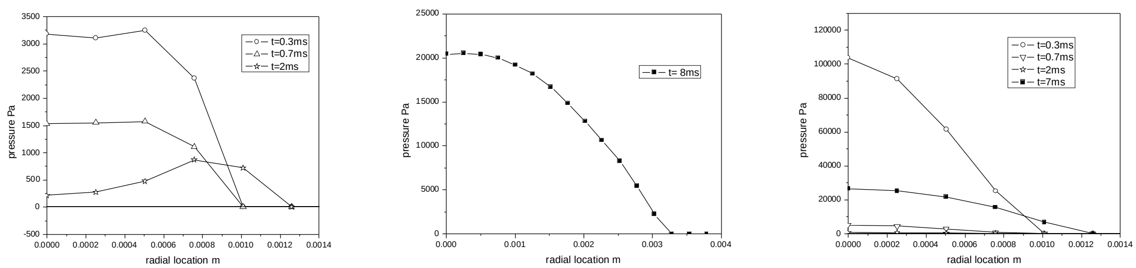

**Case A:** I partially melted **and** II completely melted
**Case B:** I completely melted **and** II partially melted
**Case C:** I partially melted **and** II partially melted
**Case D:** I completely melted **and** II completely melted

FIG. 6-Schematic representation of the four studied cases.

we present in Figure (7) the distribution of pressure at the interface of two mediums and for different time sequences. we find for the area affected by the pressure in cases D and B (high burst ), 3.2 mm is significantly higher than that of cases A and C ( equal to 1.3mm) at the moment of arrival of the second particle. Also in relation to case D the pressure distribution on the contact surface has a discontinuity between 0.0012mm and 0.0015mm; after a sudden drop in pressure and then a sudden increase, this discontinuity will reflect the time of the breakup of slip and mass loss for defective siding.

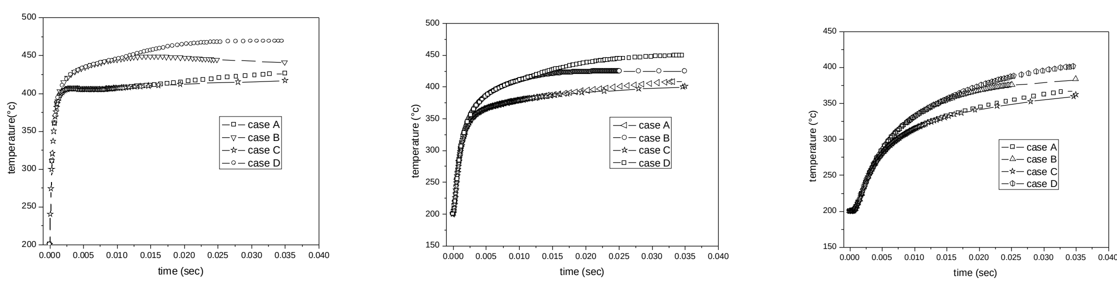



case D case C

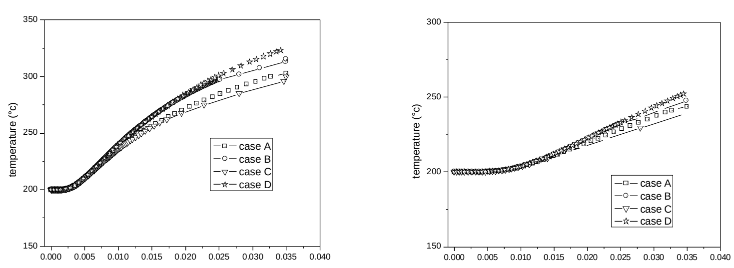



case B case A

FIG. 7- Distribution of contact pressure at the interface along the radius of the slide on a smooth substrate




at the substrate surface at 61µm in the substrate at 213.7µm in the substrate




at 488.5 µm in the substrate at 854.9 µm in the substrate

FIG. 8- Substrate history of temperature for the four cases studied

The substrate temperature in our case is the result of a balance between the heat flux transferred to the substrate by coverslip and the jet. Figures (8) show the evolution of temperatures in the substrate below the point of impact of the drop as a function of time. These temperatures are taken at the substrate surface (y = 0), and rentals on the z below the surface of the substrate.

In the earliest moments after the first contact of the drop with the target, the substrate temperature at the point of impact rises rapidly and at the same speed for the four cases, one can say that the substrate temperature is mainly governed by impact of the first drop.

The simulation results show that the temperature of case D increases more rapidly. As a result, the strip is cooled more rapidly by conduction which promotes the formation and propagation of the solidification front in the lower part of the slide. The rest of the high kinetic energy is in the upper layers, and thus promotes the break. In contrast, case C, where the cooling rate is slow, there is a decrease in the phenomenon of bursting.

## Conclusion:

The present model is used to investigate the impact of partially molten Aluminum alloy 380 particle on a H13 tool steel substrate. The model is in good agreement with the experiment and previous numerical data.
the present model has shown that the surrounding gas temperature has a great effect on the shape of the splitting. When this temperature is above the melting temperature of the particle, a delay of the solidification of splat is observed allowing the shrinkage of the splat. However, a high gas temperature can lead to a good adhesion of the splat with the substrate due to a relatively improvement of the contact pressure comparing to low gas temperature case.
A deposit made by plasma spraying result of a successive stacking of individual lamellae which constitute the cornerstone of the depot construction.
This part of the work which presents state of the art with respect to the impact of two successive drops on a target; Particularly on studies of phenomena associated with the molten particles. The analysis shows that the impact of the second drop transfers the heat to the first lamella, under a pressure, a phenomenon that plays a decisive role in the final morphology of the lamellae; by which the initial kinetic energy is converted more or less rapidly at viscous forces and surface energy.

## Reference:

[1] J. R. Davis et al. (Eds.), first ed., Handbook of thermal spray technology, ASM international, Materials Park, OH, 2004
[2] P. Fauchais, A. Vardelle, B. Dussous, Quovadis thermal spraying?, J. Thermal spray technology 10(1) (2005) 44-66
[3] A. Abdellah El-hadj, N. AitMessaoudène, " Comparison between Two Turbulence Models and Analysis of the Effect of the Substrate Movement on the Flow Field of a Plasma Jet", Plasma Chemistry and Plasma Processing, Vol. 25, No. 6, pp. 699-722, 2005.
[4] J. Cedelle, M. Vardelle, P. Fauchais, « Influence of stainless steel substrate preheating on surface topography and on millimeter and micrometer sized splat formation », Surface and coating technolgy 201 (2006) 1373-1382
[5] M. Xue, Y. Heichal, S. Chandra, J. Mostaghimi, « Modeling the impact of a molten droplet on a solid surface using variable interfacial thermal contact resistance", J. Mater sci. (2007) 42: 9-18
[6] L. Xu, W.W. Zhang, S.R. Nagel, Drop splashing on a dry smooth surface, Phys. Rev. Lett., 94, (2005)18
[7] A. Abdellah El-Hadj, M. Zirari, N. Bacha, Numerical analysis of the effect of the gas temperature on splat formation during thermal spray process, Appl. Surf. Sci. 257 (2010) 1643–1648.
[8] M. Zirari, A. Abdellah El-Hadj, N. Bacha, Numerical analysis of partially molten splat during thermal spray process using the finite element method, Appl. Surf. Sci. 256 (2010) 3581–3585.
[9] Manual of Ansys ver 11, Ansys.inc, USA
[10] R. Ghafouri-Azar, S. Shakeri, S. Chandra, J. Mostaghimi, "Interactions between molten metal droplets impinging on a solid surface", International Journal of Heat and Mass Transfer 46 (2003) 1395-1407